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M. Key, K. Akli, F. Beg, R. Betti, D. S. Clark, S. N. Chen, R. R. Freeman, S. Hansen, S. P. Hatchett, D. Hey, J. A. King, A. J. Kemp, B. F. Lasinski, B. Langdon, T. Ma, A. J. MacKinnon, D. Meyerhofer, P. K. Patel, J. Pasley, T. Phillips, R. B. Stephens, C. Stoeckl, M. Foord, M. Tabak, W. Theobald, M. Storm, R. P. J. Town, S. C. Wilks, L. VanWoerkom, M. S. Wei, R. Weber, B. Zhang

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On point designs for high gain fast ignition

**M H Key[1], K Akli[2], F Beg[5], R Betti[6], D S Clark[1], S N Chen[5], R R Freeman[2,3]
S Hansen[1], S P Hatchett[1], D Hey[2], J A King[2], A J Kemp[1], B F Lasinski[1]
B Langdon[1], T Ma[5], A J MacKinnon[1], D Meyerhofer[10], P K Patel[1], J Pasley[5]
T Phillips[1], R B Stephens[4], C Stoeckl[6], M Foord[1], M Tabak[1], W Theobald[6]
M Storm[6], R P J Town[1], S C Wilks[1], L VanWoerkom[3], M S Wei[5], R Weber[3]
B Zhang[2]**
[1]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[2]Department of Applied Sciences, University of California Davis, Davis, CA 95616, USA
[3]Ohio State University, Columbus Ohio, 43210, USA
[4]General Atomics, San Diego, CA, 92186, USA
[5] University of California, San Diego, San Diego, CA, 92186, USA
[6]Laboratory of Laser Energetics, University of Rochester, NY, USA

E-mail key1@llnl.gov

Abstract. Fast ignition research has reached the stage where point designs are becoming crucial to the identification of key issues and the development of projects to demonstrate high gain fast ignition. The status of point designs for cone coupled electron fast ignition and some of the issues they highlight are discussed.

1. Introduction

Demonstration of laser driven inertial confined fusion with central hot spot (CHS) ignition is expected when the National Ignition Facility (NIF) in the USA and the Laser Mega Joule (LMJ) in France become operational within the next few years. Preparations for ignition are based on point designs, which rigorously specify all requirements for the experiments including the target design, the target fabrication, the laser performance, the target alignment and the diagnostic instrumentation.

Inertial confined fusion by laser driven fast ignition (FI) is much less mature[1]. Research has been at the level of concept exploration and there are as yet no facilities under construction aimed at demonstrating high gain FI. The potential for higher gain at reduced driver energy is however motivating more aggressive projects, which will enable integrated FI experiments at higher laser energies closer to ignition conditions, notably the Firex I project in Japan, Omega EP and NIF ARC in the USA and Petal in France. Conceptual designs for full-scale high gain fast ignition facilities are being explored ranging from dedicated new facilities, HiPER in Europe and Firex II in Japan, to adaptation of major ignition facilities such as NIF.

This new phase of fast ignition research is bringing about a need to transition from small-scale research on aspects of the physics, to the development and use of point designs for high gain FI. These will become the primary method for identifying key physics issues and advancing FI studies to the building of facilities capable of high gain FI. There are several approaches to FI, which are at varied states of development[1] including cone coupled electron ignition, proton (or other ion) ignition via a cone, channelling and hole boring, super penetration and impact FI. The discussion here is limited to the most mature of these, cone coupled electron ignition.

2.Point design status and issues

Progress in FI research has already established some generic aspects of point designs. The required density radius product ρr of the compressed DT fuel is typically 1.7 to 2 gcm^{-2} for sufficient thermonuclear burn efficiency. Densities in the range 300 to 500 gcm^{-3} allow direct drive compression with driver energy <200kJ and gains approaching 100x which are very attractive relative to the mega-joule driver energy and 10 to 20x gain for typical CHS ignition point designs. Target designs and implosion drives producing the required imploded fuel parameters with a minimal central hollow have been developed using one-dimensional hydrodynamic models. In broad terms these use lower drive pressure and velocity and thicker shells with less fluid instability than CHS point designs[2].

Modelling of ignition has shown the minimum requirements for the ignition hot spot[3,4]. For example at 300 gcm^{-3}, these are 18 kJ of energy delivered in 23 ps in a diameter of 36 μm at an intensity of 1.1×10^{20} Wcm^{-2}. The diameter of the compressed fuel is 133 μm for $\rho r = 2 gcm^{-2}$, significantly more than the hot spot diameter. Hydrodynamic similarity considerations and the requirement that the imploding plasma should not penetrate the tip of the cone, dictate that the cone tip to dense fuel separation be similar to the dense fuel diameter. Then the ignition hotspot would subtend only 0.057 sterad at the cone tip. This poses a problem since transport of the electrons between the cone tip and the hot spot is divergent[5] and the coupling efficiency is therefore proportional to the subtended solid angle.

Better coupling efficiency may be obtained using non-ideal ignition[4] in which the hot spot diameter is 3x wider than the minimum. If the fuel density is raised to 500 gcm^{-3} the fuel diameter is reduced to 80μm and the hot spot diameter is increased to 60 μm. The ignition energy is unchanged at 18kJ, the pulse duration is reduced to 14 ps and the intensity is reduced to 4.6×10^{19} Wcm^{-2}. The solid angle subtended by the hot spot is increased 7.7x to 0.44 sterad with major potential for increased coupling efficiency.

The development of FI point designs is proceeding using both indirect and direct drive. Indirect drive is more compatible with NIF and LMJ and has potential for a two-sided configuration with cone coupled ignition from one side and hohlraum drive from the other, of interest for a fusion energy power plant[6]. Direct drive is more efficient and therefore attractive for new projects such as Firex II and HiPER, which aim to use driver energy <200kJ. Both approaches require major 2D and 3D hydrodynamic design effort on detailed issues including minimizing the thickness and separation from the hot spot of the cone tip and minimizing the low density hollow in the imploded fuel.

Radiation cooling due to high Z contamination of DT can quench ignition and reduce gain. Target fabrication choices are affected, for example the attractive fabrication option of DT wetted CH foam. Here 10 $mgcm^{-3}$ is the maximum density of the foam for negligible increase of the ignition threshold but 50 $mgcm^{-3}$ is the lowest density that has been fabricated to date[7]. Entrainment of high Z material ablated from the cone is a hydrodynamic design issue that can be mitigated with low Z coating of the outer surface of the cone but for indirect drive it is a significant hydrodynamic design problem due to strong ablation by M and L shell radiation in the hohlraum penetrating the imploding capsule.

The electron source characteristics are critical. The average range of the electrons is optimized[4] at 1.2 gcm^{-2}. This corresponds to electron energy of 2 MeV[8]. The electron energy is important because the required ignition energy increases almost linearly with the energy[4]. The electron energy spectrum and laser to electron energy conversion efficiency are not so well understood but are determined by the laser intensity and wavelength, the preformed plasma and the focal spot size and cone geometry. A widely used model gives an average hot electron energy E_h similar to the ponderomotive potential so that E_h= 2MeV is obtained with intensityx (wavelength)^2= $2 \times 10^{19} Wcm^{-2} \mu m^2$.

The required laser intensity depends on the laser energy to hot spot coupling efficiency, which is a major uncertainty for FI. For example if it were 20% as in the first integrated FI experiment[9] with a subtended solid angle close to 1 sterad, and the cone tip size were 60 μm equal to the previously discussed hot spot diameter, the required laser intensity would be 2.3×10^{20} Wcm^{-2}. The wavelength required for a ponderomotive potential of 2MeV is then 0.3 μm. Operation of a 1μm laser at its 2^{nd} or 3^{rd} harmonic is possible but not developed for high energy ps pulses, though point design studies for HiPER have for example assumed 2^{nd} harmonic operation to meet the simultaneous constraints of required ignition intensity and electron energy.

The ponderomotive potential is not however a good predictor of the electron energy in FI because of the effects of light pressure on the preformed plasma density gradient. This pressure is 100 Gbar at $2\times10^{20}Wcm^{-2}$. Combined with the required ignition pulse duration >10 ps it pushes back the critical density and sweeps up preformed plasma to form a very steep density interface with a strong shock driven into the cone tip. 2D Particle in cell (PIC) modelling of the laser plasma interaction in a cone shows this density profile steepening and predicts a significant reduction of the mean electron energy relative to the ponderomotive potential[10]. There is also a reduction of laser absorption efficiency A_l. PIC modelling in 1D has shown that for more extended preformed plasma scale length the steepening takes longer and there is a transient phase with higher E_h and A_l followed by a longer equilibrium phase with reduced E_h and A_l. Such modelling enables estimation for example of the laser intensity and preformed plasma density gradient which for 1μm laser wavelength give the previously discussed $4.6\times10^{-19}Wcm^{-2}$ electron beam intensity with E_h=2MeV. An exponential density gradient with 10 μm scale length and the previously estimated intensity of $2.3\times10^{20}Wcm^{-2}$ comes close[11]. Cavitation instability at the critical density may however modify the results significantly. Furthermore current laser facilities are not capable of generating the FI required intensity and pulse length so experimental verification is lacking. There is therefore a crucial need to conduct computer intensive 2D and 3D PIC modelling and to use next generation multi-kJ short pulse lasers to gain an adequate understanding of E_h and A_l for FI relevant conditions.

In cone coupled FI the electrons are generated inside the hollow cone, which introduces additional considerations for point designs. Early studies suggested that absorption at oblique incidence on the walls of the cone generates a magnetically guided flow of electrons along the inner surface to the cone tip with a consequent increase in electron flux density[12]. Experiments with oblique irradiation of planar foil targets have shown an electron beam in vacuum tangential to the surface[13]. The amount of energy carried by this beam has not however been established and more recent observations[14] of a 40x increase in reflected energy and a 20x decrease in Kα yield from Cu foil targets at 15° glancing incidence relative to normal incidence, suggest that the cone may actually be more effective as a plasma mirror enhancing intensity at the cone tip by reflection of laser energy from the cone walls. Relevant here is that single reflection coupling to the cone tip for a parallel beam increases the beam area coupled to the tip by almost one order of magnitude for very oblique angles. Optimum cone angle, cone tip area and surface finish are all point design issues to be determined more precisely.

Scattering of electrons passing through the cone tip can increase the divergence of the source and there is a trade off between more thickness to allow reduced separation from the hot spot and less thickness to reduce scattering. Early work has used Au cones but lower Z and lower ρ may be better. From Monte Carlo (MC) modelling illustrated in figure1, the thickness of Au for which the major fraction of ignition relevant electrons are scattered within <1 sterad is ~15 μm. Scattering diminishes rapidly for lower Z offering lower Z design options to optimize the cone tip for maximum resistance to penetration with tolerable scattering.

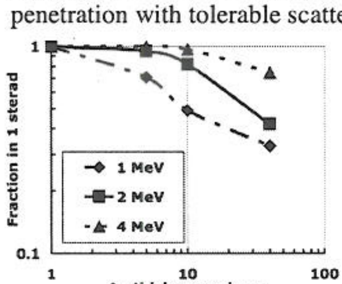

Figure1. MC modelling of the fraction of a mono-energetic parallel electron beam scattered in <1sterad

Preformed plasma in the cone due to amplified spontaneous emission affects the electron source and in typical systems it is 10^{-4}

of the main pulse energy, but for full scale FI that becomes ~10J. Recent experiments with a 150 J, 1 pHs laser have shown that Kα fluorescence in a Cu cone is changed from localized emission at the cone tip for a 15 mJ pre-pulse to uniform emission from the whole cone at 1J pre-pulse, suggesting limited tolerance of pre-pulse energy. It is not clear however whether the huge light pressure impulse in full scale FI would change this behaviour. Harmonic conversion is one way to reduce ASE but is not developed for high-energy ps pulses. Pre-pulse suppression with non-linear devices in the laser front end is another option where there is R&D progress.

The intensity pattern in the focal spot is a specific feature of CHS point designs but in FI it has so far been largely neglected. Is it better for example to deliver all the laser energy directly to the cone tip or can a significant fraction be reflected off the cone wall to increase the tolerable focal spot diameter? Full scale FI requires the combination of multiple beams at a single focal spot where the phasing of the beams will determine the focal spot pattern, ranging from an ideal uni-phase spot to more complex interference patterns. Laser technology solutions for phase control must be linked to design requirements to specify the focal spot in FI point designs.

Benchmarked integrated modelling is required for point designs to reach maturity. Large scale PIC modelling of and idealized laser/cone /compressed plasma configuration has given useful insights but limited to for shorter pulses with little capacity to study the effect of parameter changes[10]. Hybrid PIC modelling with heuristic injected electrons and an idealized compressed plasma has allowed study of sensitivity of the ignition energy to electron angular divergence and the cone tip to hot spot separation and has identified magnetic collimation occurring for lower divergence angles[15]. Fully integrated models combining 2D hydrodynamics, PIC laser plasma interactions and hybrid PIC or Fokker Planck transport are being developed[6, 11] and will be bench marked in the upcoming new phase of integrated experiments at Omega EP, Firex I, NIF ARC and Petal.

In conclusion point designs are now crucial in the development of fast ignition. Their status in cone coupled electron ignition has been discussed and key issues identified. They are less developed but similarly important for the other approaches to FI some of which still have no overall point design.

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